

A Study of the Effects of Atmospheric Phenomena on Mars Science Laboratory Entry Performance

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At Earth during entry the shuttle has experienced what has come to be known as “potholes in the sky” or regions of the atmosphere where the density changes suddenly. Because of the small data set of atmospheric information where the Mars Science Laboratory (MSL) parachute deploys, the purpose of this study is to examine the effect similar atmospheric pothole characteristics, should they exist at Mars, would have on MSL entry performance. The study considers the sensitivity of entry design metrics, including altitude and range error at parachute deploy and propellant use, to pothole like density and wind phenomena.

Nomenclature

<i>MOLA</i>	=	Mars Orbiter Laser Altimeter
<i>MSL</i>	=	Mars Science Laboratory
<i>POST2</i>	=	Program to Optimize Simulated Trajectory 2
<i>EDL</i>	=	Entry, Descent, and Landing

I. Introduction

AMONG the challenges of landing spacecraft on Mars is the inability to test an end-to-end mission prior to landing on the planet. Therefore simulations are relied on heavily by design engineers. In the simulations, engineers have to account for all known uncertainty and include robustness for the unknown. There are a number of known uncertainties that must be mitigated, but among them, one of the largest is the atmospheric density and wind profiles. This is because the Mars atmosphere is highly variable and not well characterized. The observed and in-situ atmosphere data set for Mars over all latitudes, seasons and local solar times is sparse at altitudes below 90 km. In the region of the atmosphere between 5 and 30 km, where the Mars Science Laboratory (MSL) entry vehicle decelerates on the parachute, the only data is derived from the six entry profiles (Viking 1 and 2, Pathfinder, MER Spirit and Opportunity, and Phoenix). Therefore, scientists and engineers rely heavily on global circulation models, mesoscale models and large Eddy simulations [Ref. 1,2,3] to characterize this region of the atmosphere. Understanding the region is critical to accurately quantifying both the timeline and altitude margins for entry, descent and ultimately a successful landing.

It is the unknown nature of the Mars atmosphere below 90 km that prompted the study to analyze and understand the effects of specific atmospheric phenomena that have been observed at Earth. During shuttle orbiter entry, a pothole-in-the-sky [Ref. 4, 5] phenomenon has been observed in which densities change up to 60% [Ref. 6] over short durations. Therefore a systematic analysis of the Mars atmosphere was performed to evaluate the effect these potholes (decreases) or bumps (increases) in both density and wind might have on the entry performance for MSL. The study focuses on the region between 10 and 35 km above Mars Orbiter Laser Altimeter, MOLA, areoid, which has atmosphere properties similar to ~200,000 ft (60 km) at Earth. A description of the nominal trajectory and the assumptions made for the density and wind variations are provided below.

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II. Procedure

The study considers trends in nominal MSL entry trajectories only. The nominal 6 degree of freedom (DOF) trajectory selected for this study, denoted as 07-16, includes a rover mass of 3254 kg in a 4.5 m aeroshell using a single 21.5 m supersonic parachute and a 6 second entry guidance drag filter. The vehicle is targeted to arrive at Mars on August 9, 2010 and land at Nili Fossae Trough site at 21°N, 74°E with an elevation of -0.6 km relative to the reference MOLA areoid. See Fig. 1.

The atmospheric variations or swaths in the sky are modeled in the following way. Density variations are represented as a step function of ± 30 percent of the nominal density. The wind speeds varied, also as a step function, from a 50 m/s head wind to a 50 m/s tail wind in increments of 25 m/s. The winds, in this case, are designed to be exactly opposite of (in the case of a head wind) and exactly along (for a tail wind) the atmospheric relative velocity vector, regardless of vehicle azimuth.

The vertical depth of the atmosphere disturbance where the density or wind variation takes place are swaths of 1, 2, 5, 8 and 10 km occurring in the atmosphere range between 10 to 35 km above the MOLA areoid. Swaths were analyzed in one kilometer increments. For example, the 1 km swath widths extended from 10 to 11 km, 11 to 12 km up to 34 and 35 km above the areoid; likewise, the 10 km swaths extended from 10 to 20 km, 11 to 21 km up to 25 to 35 km above the areoid. An example of the modeled density phenomena can be seen in Fig. 2. The figure shows in black the nominal density profile from 0 to 40 km above the areoid. The blue dot dash lines are 30 percent higher and

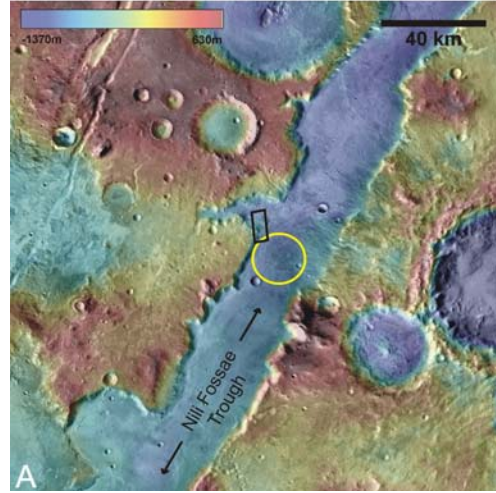


Figure 1. Nili Fossae Trough. MOLA Elevation map of the potential MSL landing site with a circle to denote the nominal landing location ellipse.

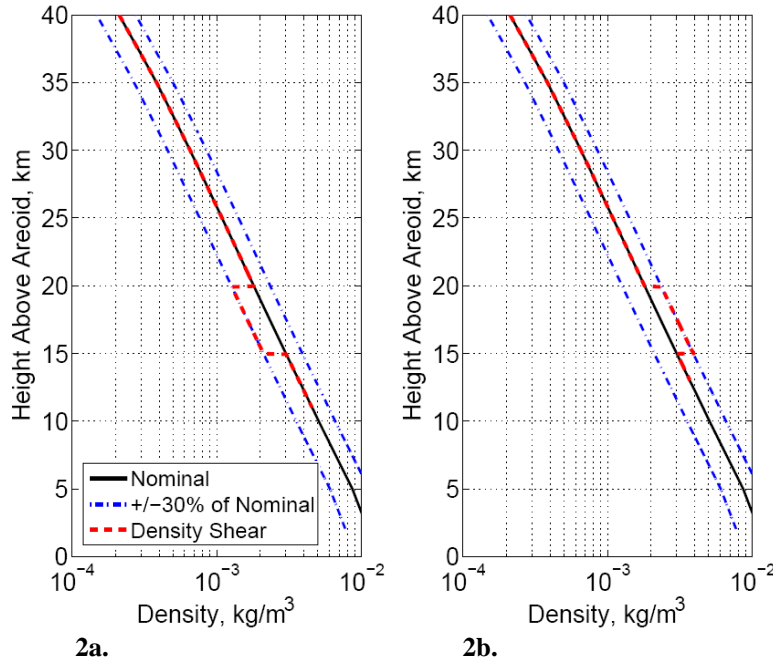


Figure 2a and 2b. Pothole Model Definition. The plot depicts density vs. altitude above areoid with Fig. 2a illustrating a “pothole” of 30 % low density (red line) whereas Fig. 2b shows a “bump” of 30 % high density.

lower density than the nominal. The red line in Fig. 2a shows a 5 km “pothole” (lower density) located between 15 and 20 km with 30 percent lower density than the nominal trajectory. Likewise the red line in Fig. 2b shows a 5 km “bump” (higher density) at the same altitude.

A similar example of the modeled wind phenomena is shown in Fig. 3. The wind analysis was performed on two different nominal cases. The first, shown in Fig. 3a, is a wind shear applied to a nominal with no nominal wind. The second, Fig. 3b, has the wind shear applied to the nominal trajectory which includes a nominal wind. In the latter case, the nominal wind effectively produces an additional offset from the nominal no wind trajectory that will be evident in the results.

Due to the characteristics of the MSL trajectory, the vehicle dives into the atmosphere quickly then levels off and flies nearly horizontal for more than a minute of flight. Therefore, depending on where the shear is applied, the vehicle may remain in the swath for significant amount of time resulting in large impacts

on the considered metrics, parachute deploy altitude, propellant and range error. Figure 4 shows a plot of the altitude versus time for the nominal trajectory for the case with the largest swath (e.g. 10 km) located at the lowest altitude considered in the study (e.g. between 10 and 20 km above MOLA). For this example the trajectory spends almost 150 second encountering the disturbance. All study cases were run using the Program to Optimize Simulated Trajectories (POST2) [Ref. 7]. The results for each analysis are provided below.

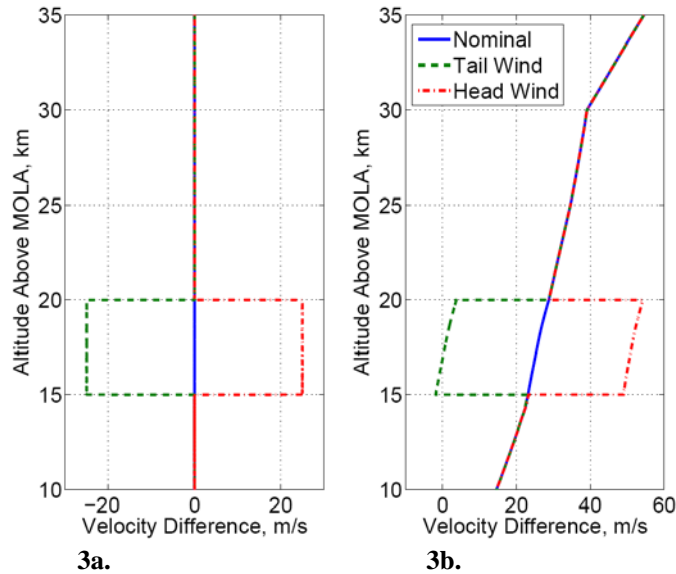


Figure 3. Wind Shear Illustration. Wind vs. altitude above areoid. Figure 3a is a wind shear applied to a nominal with no nominal wind. Figure 3b. The wind shear is applied to the nominal trajectory which includes a nominal wind.

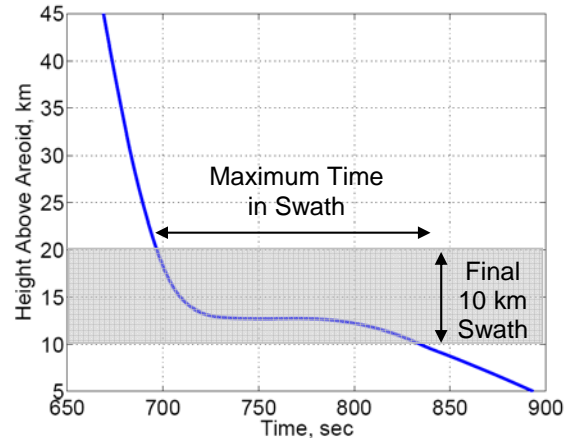


Figure 4. Altitude vs. Time for the nominal 07-16 trajectory. Figure 4b illustrates the application of an atmosphere swath 10 km thick between 10 and 20 km in altitude above the MOLA areoid.

III. Results

A. Density Sheer Results

The POST2 MSL entry simulation was run for each of the density swaths described above. The altitude at parachute deploy and time in swath results for the 1 km “deep” density “pothole” analysis is shown in Fig. 5a. One kilometer density swaths located above 15 km above the areoid have little impact on the altitude at chute deploy. A few trajectories passing through the pothole between 16 and 22 km above the MOLA areoid actually have slightly higher altitudes at parachute deploy compared to the nominal. Closer inspections of the individual trajectories show that the higher than nominal parachute deploy altitudes result from different lofting periods due to the particular location of the pothole in the trajectory. Lofting is defined as the time in the trajectory when the flight path angle is positive. As the trajectory flies through swaths below 15 km above the areoid in the denser region of the atmosphere, the impact of passing through a 1 km pothole becomes evident in the increased time in the swath, as well as in the increased loss of altitude at parachute deploy. Figure 5 contains a complete set of the results for each of the swath widths considered (2, 5, 8, and 10 km deep potholes). The largest impact of a 30% low density swath was observed in the 5 km “deep” pothole existing between 10 and 15 km above the areoid. This trajectory spent almost 50 seconds in the swath and resulted in a 4 km reduction in altitude at parachute deploy. See Fig. 5c. Therefore, depending on the location and width of the lower density swath, parachute deploy altitude could increase from the nominal by as much as 1.5 km or decrease up to 4 km. It should be noted that in some cases, the parachute is deployed before passing completely through a density swath, which primarily occurs in density swaths that are large and near 10 km above MOLA areoid. For those cases no time in swath is recorded.

A plot of the distance or range traversed in each swath is shown in Fig. 5f. For the density pothole (30% low density) analysis, the range covered in any swath width considered here was between 5 and 90 km. For reference the nominal trajectory had about 620 km total down range from atmospheric entry to parachute deploy.

Propellant usage and range error to target at parachute deploy are also provided for the 30% low density sheer cases in Fig. 6 a to e. Solid horizontal lines denote nominal values for reference. No trend is identified in propellant use for the different swath sizes. The maximum difference from the nominal is only 5 kg. Range error, the distance between the actual and the desired parachute deploy location, is not affected by potholes of any width above 30 km

above the areoid. However range error does increase significantly as the swaths move lower in altitude above the MOLA areoid and can be as large as 14 km. Range error that large translate into touch down miss distances and may have significant implications on achieving landing within 10 km of a desired target.

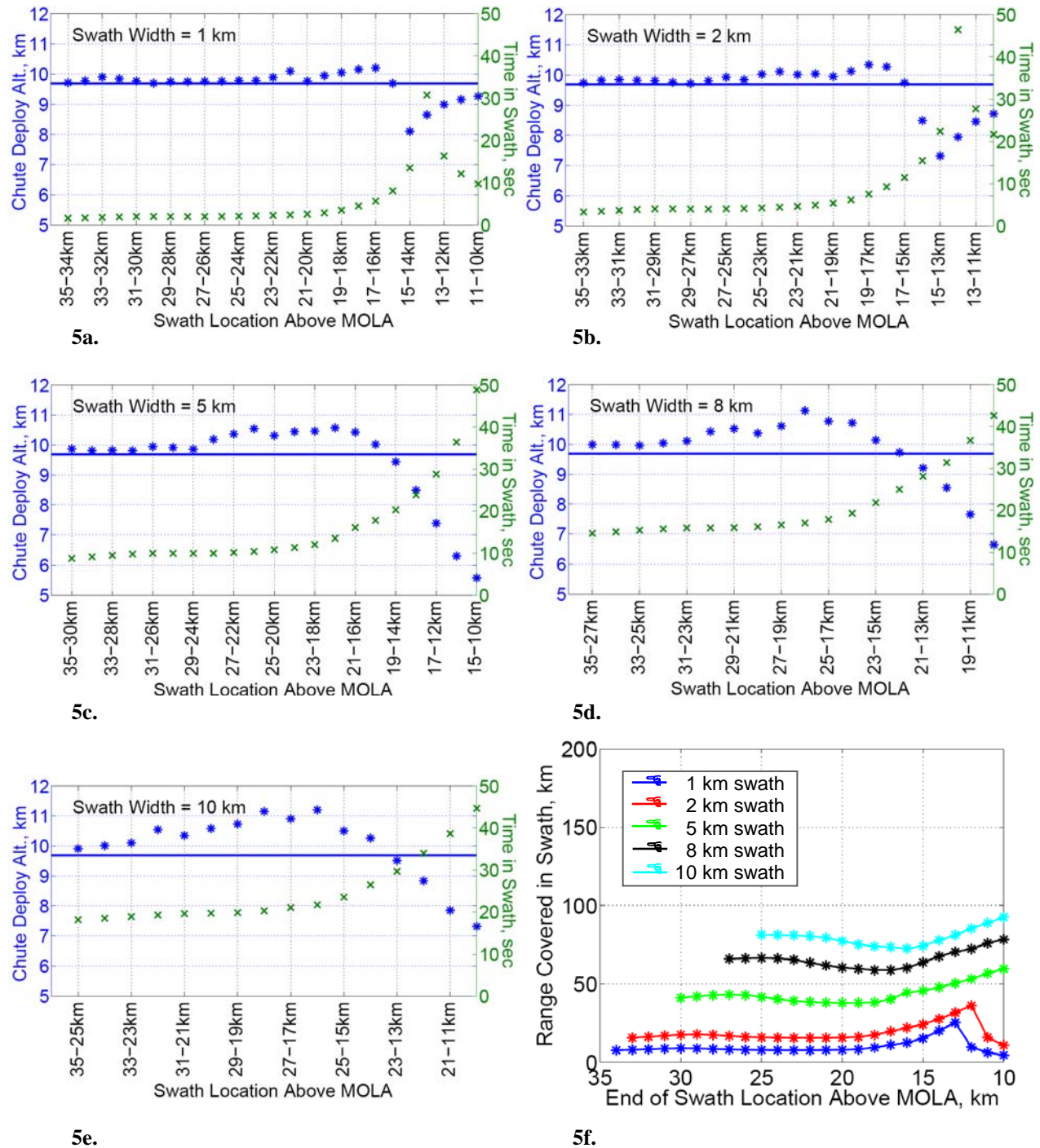
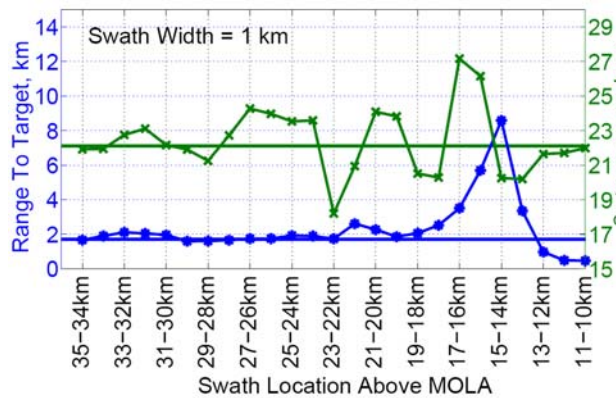
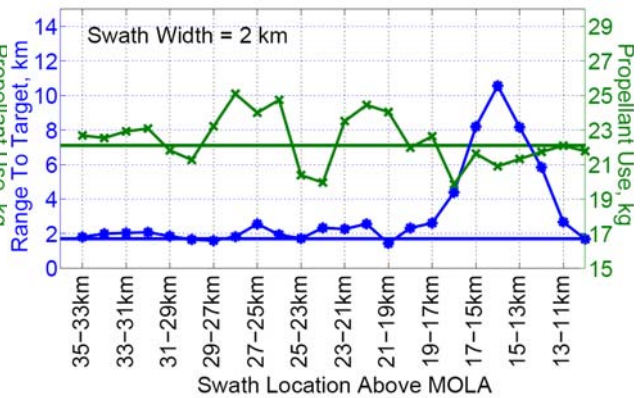


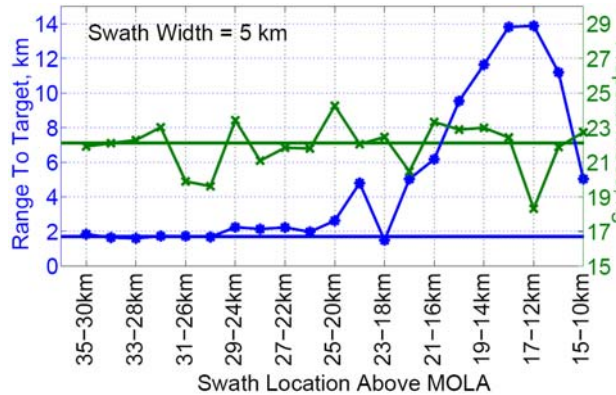
Figure 5. Density Potholes (-30% density) Parachute Deploy Altitude and Time in Swath. The left axis in Fig. a to e correspond to the final altitude at parachute deploy for each pothole considered. The nominal value is denoted with a solid line. The x symbols, corresponding to the right axis, denotes the time in swath for each case. Figure 5f shows the total distance traversed in each swath.



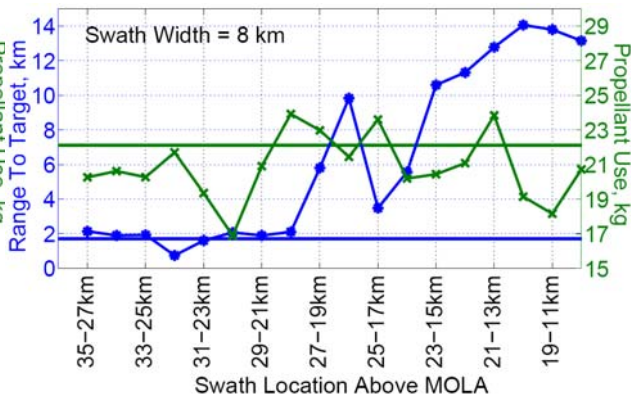
6a.



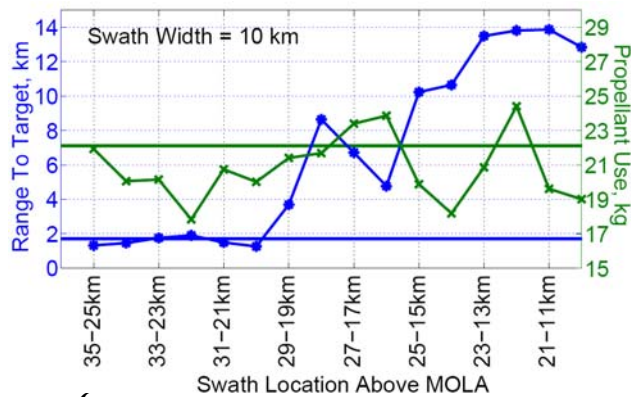
6b.



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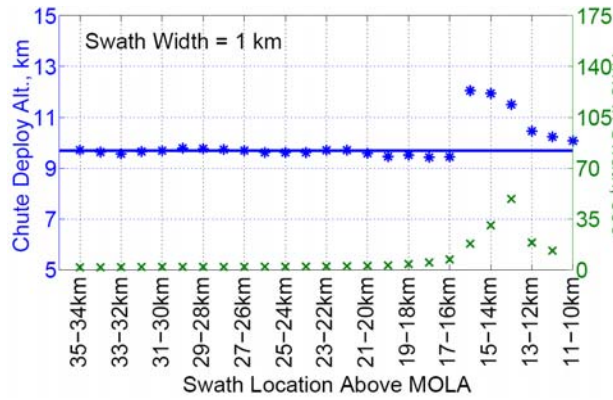


6d.

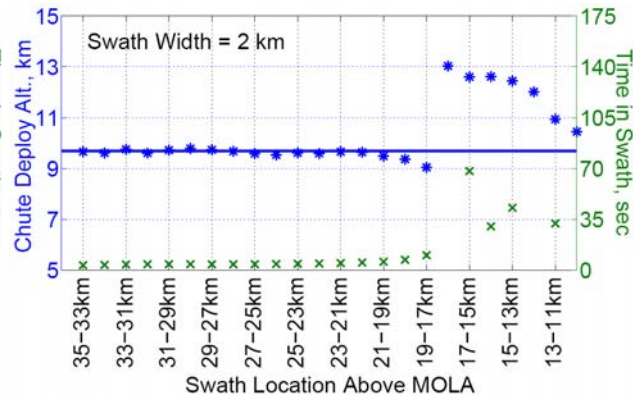


6e.

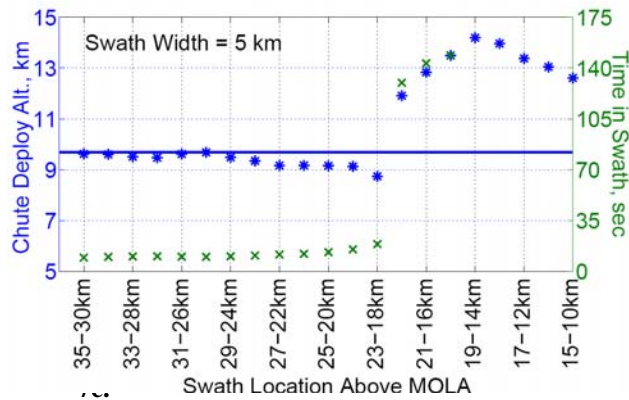
Figure 6. Density Potholes (-30% density) Range Error and Propellant Use. The left axis in Fig. a to e shows the results of range from parachute deploy target with the solid blue line corresponding to the nominal. The right axis shows the propellant use in each swath with the green solid line denoting the nominal value.



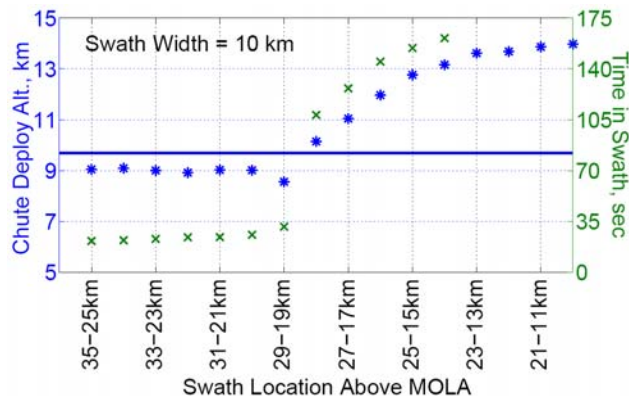
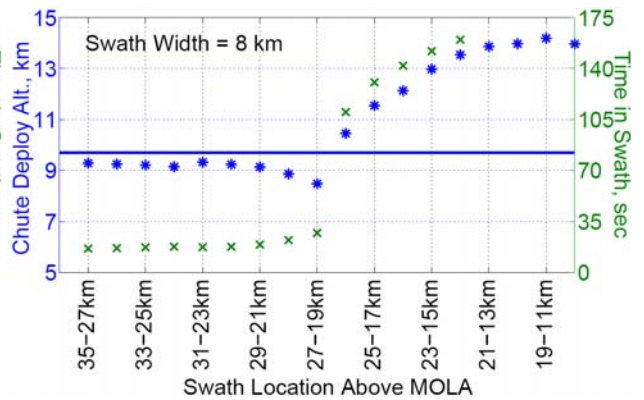
7a.



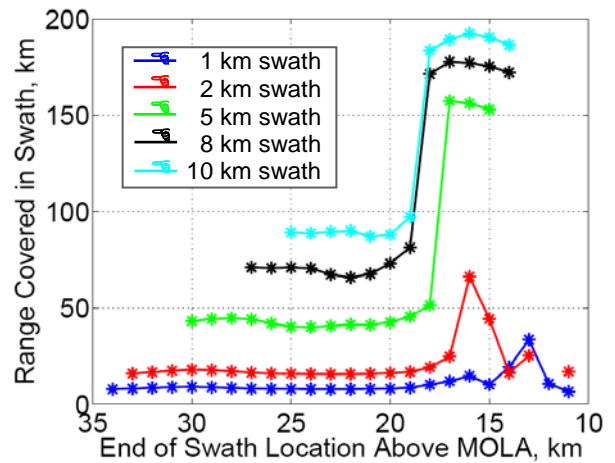
7b.



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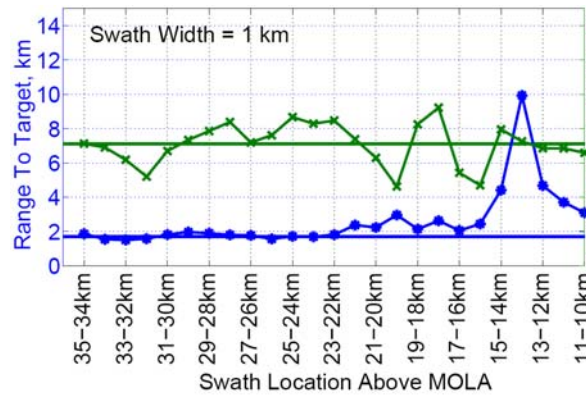


7e.

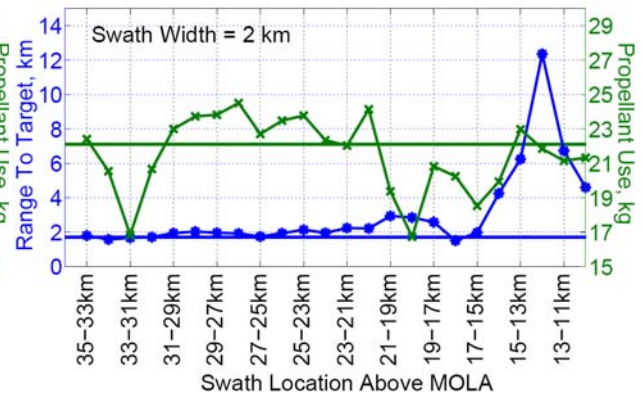


7f.

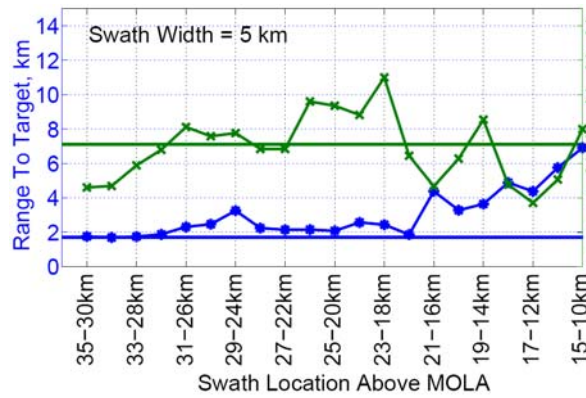
Figure 7. Density bumps (+30% density) Parachute Deploy Altitude and Time in Swath. The left axis in Fig a-e correspond to the final altitude at parachute deploy for each bump considered. The nominal value is denoted with a solid line. The x symbol, corresponding to the right axis, denotes the time in swath for each case. Fig. 7f shows the distance traversed in each swath.



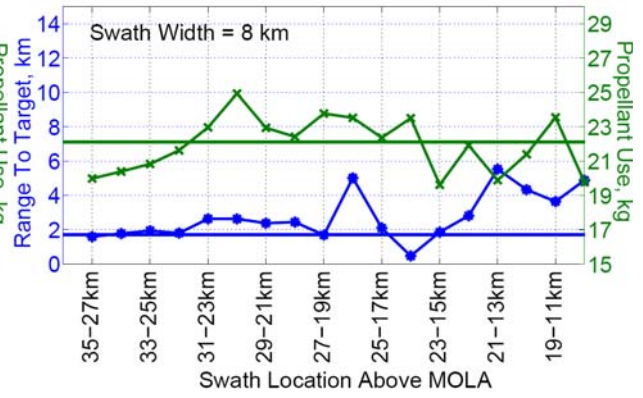
8a.



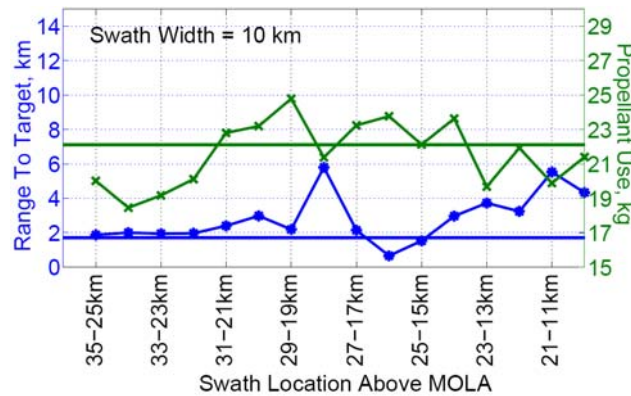
8b.



8c.



8d.



8e.

Figure 8. Density bumps (+30% density) Range Error and Propellant Use. *The left axis shows the results of range from parachute deploy target with the solid blue line corresponding to the nominal. The right axis shows the propellant use with the green solid line denoting the nominal value.*

The analysis was repeated for the +30% density sheers or “bumps”. The results can be seen in Figs. 7 and 8. As expected, sheers of increased density do significantly increase the altitude at parachute deploy as much as 4 km when the sheers occur below 20 km above the areoid. Those cases traverse much more range in respective swaths, almost double, than the -30% density shear cases. See Fig 7f. Yet, in most cases, the range error at parachute deploy is smaller due to increased vehicle performance in the increased density regions. Like the 30% low sheers, no trends in propellant usage for the +30% density cases are identified.

However, despite the assumptions made thus far, it may be more realistic to consider a pothole not as a spatial phenomena but rather a temporal one. An atmospheric phenomenon encountered for longer than a few seconds is likely to be more correctly characterized as a gravity or other wave phenomena, not a pothole. To demonstrate the impact on parachute altitude from a short duration disturbance, consider the case that had the largest loss of altitude in the shortest time in swath (i.e. 1 km swath between 14 and 15 km for the 30% low density in Fig. 5a). The case experienced a loss of 1.6 km from a 13.5 s while in the 30% low density swath. Consider acceptable pothole durations of 5 or even 10 seconds as shown in Fig. 9. Now assume that the density disturbance was only 5 seconds long, the loss of parachute altitude is only 0.5 km. If the duration is 10 seconds long, the loss of parachute altitude is 1.3 km. Therefore, if the assumption is made that potholes do exist in the Martian atmosphere for durations less than 5 second, the maximum negative effect of encountering a single pothole at the “worst” location based on this analysis would be a loss of 0.5 km at parachute deploy. This half of a kilometer is not likely to have an impact for MSL landing sites below -1 km MOLA, but will decrease timeline margin for landing sites above that altitude like Nili Fossae Trough.

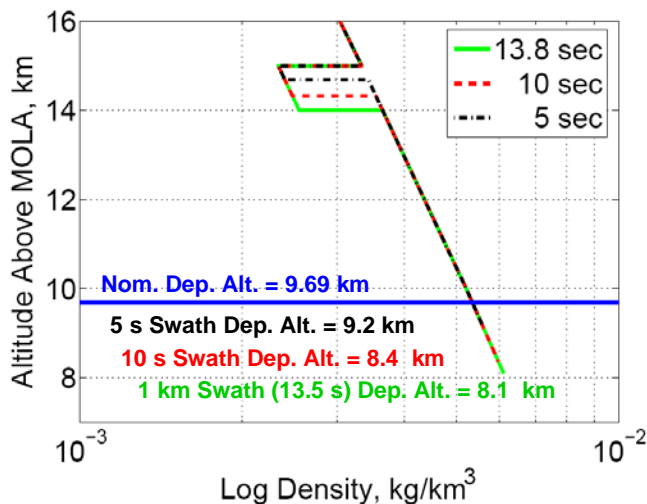
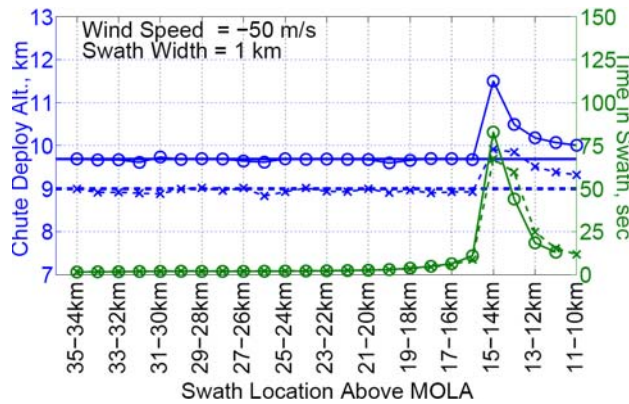


Figure 9. Altitude vs. density for the 30% low density shear located between 14 and 15 km above the MOLA areoid. Comparisons are made to swath widths of 5 and 10 seconds and resulting altitudes at parachute deploy.

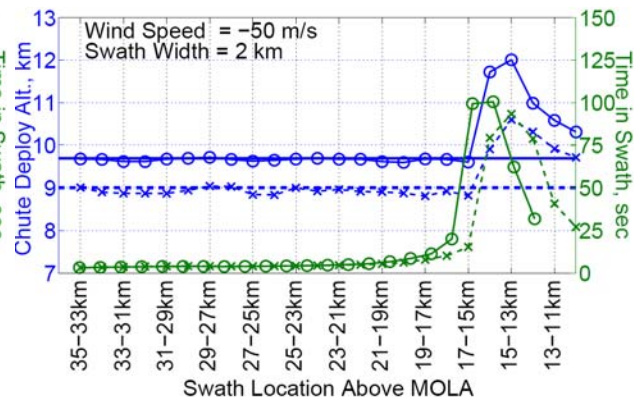
B. Wind Sheer Results

The above analysis is repeated, this time for wind sheers instead of density. The analysis uses what is considered to be worst case winds, not only in magnitude but also because they are designed to be exactly opposite of (in the case of a head wind) and exactly along (for a tail wind) the atmospheric relative velocity vector. As mentioned previously, the winds are applied as a step function at the same swath widths and locations as the density shear analysis. The winds are incremented in 25 m/s such that there are four cases; 50 m/s tail wind, 25 m/s tail wind, 25 m/s head wind and a 50 m/s head wind. The analysis was performed on two nominal cases, one that included nominal winds and one that did not. The altitude at parachute deploy and time in swath results can be seen in Figs. 10 through 13. The no wind cases are denoted with dashed lines with symbols whereas the cases with nominal winds are denoted with solid lines with symbols. The horizontal lines denote nominal values.

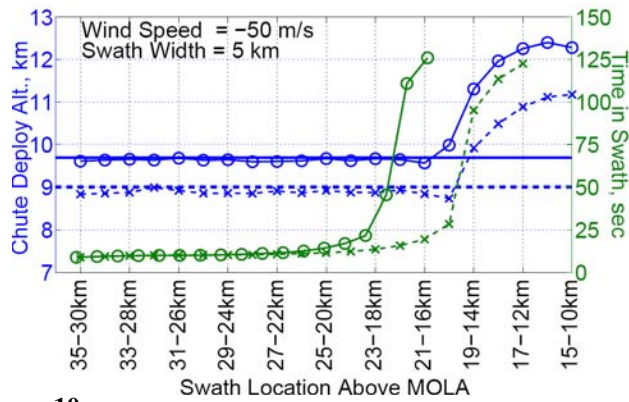
In general, the winds sheers, regardless of speed, have little effect on altitude at parachute deploy and range error at parachute deploy higher than 20 km above the MOLA areoid. However, as expected, head winds generally increase altitude at parachute deploy whereas tail winds decrease it. A 50 m/s head wind of various “depths” encountered below 20 km can increase the altitude of parachute deploy by more than 2 km as shown in Fig. 10d. A 25 m/s head wind encountered near 10 km has the effect of increasing parachute deploy altitude by only a kilometer. See Fig 11a to e. The trends are reversed for tail winds. The 25 m/s tail wind lowers the altitude by 1 km, (Fig. 12 a to e.) the 50 m/s wind lowers it by 2 km (Fig 13 a to e). It should be noted that, for the cases that gain nearly 2 km in parachute deploy altitude, the trajectory spends nearly 100 s in the swath and can traverse more than 160 km. Total range from entry to parachute deploy is nearly 620 km so for the 50 m/s head wind case encountered between 13 and 23 km above the areoid, almost a quarter of the trajectory is spent in the disturbance. As mentioned before, disturbances of this duration are probably better classified as gravity or other atmospheric waves rather than potholes.



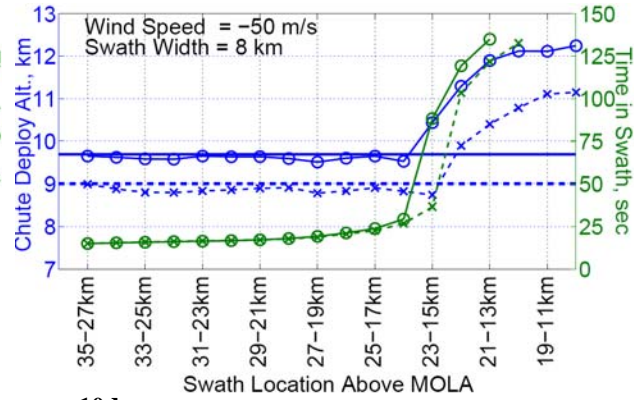
10a.



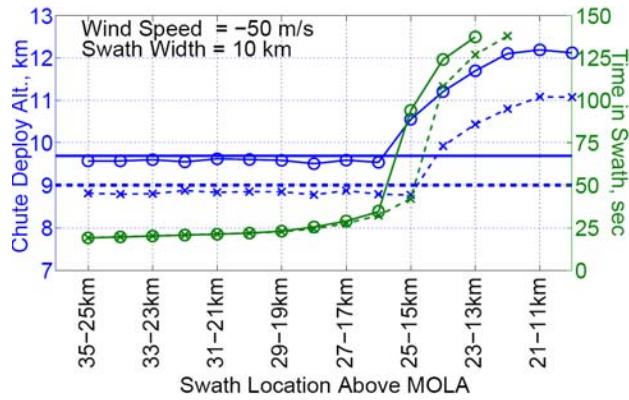
10b.



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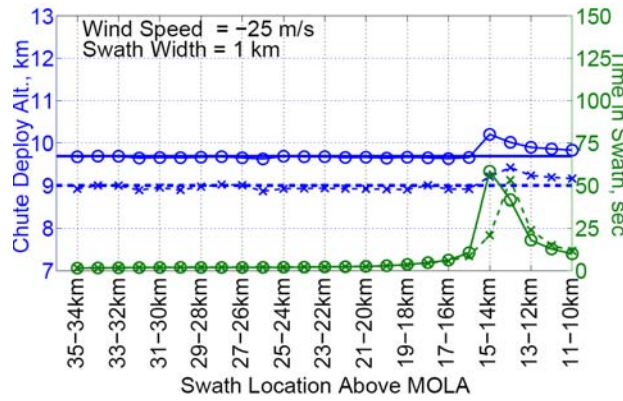


10d.

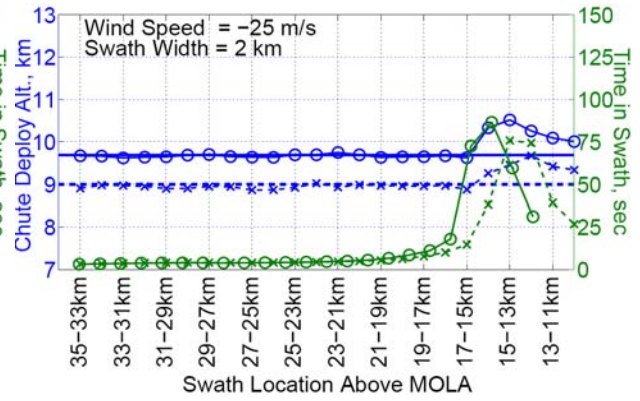


10e.

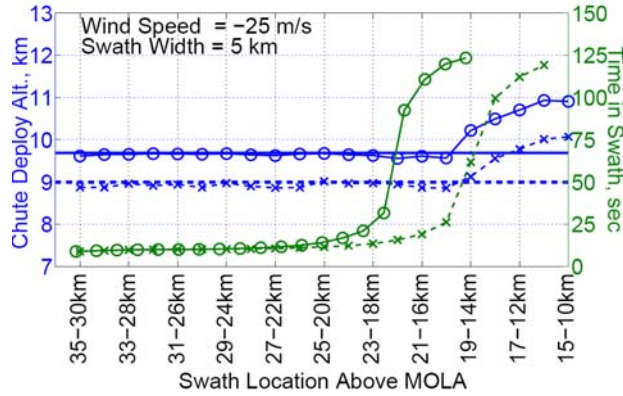
Figure 10. 50 m/s head wind. The left axis in figures a-e correspond to the final altitude at parachute deploy for each pothole considered. The nominal with nominal winds is denoted with a solid line and circles. The no wind nominal is denoted with dashed lines and an x. The axis on the right denotes the time in swath for each case.



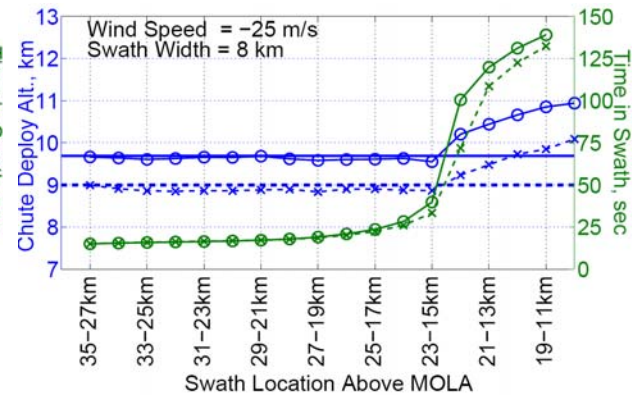
11a.



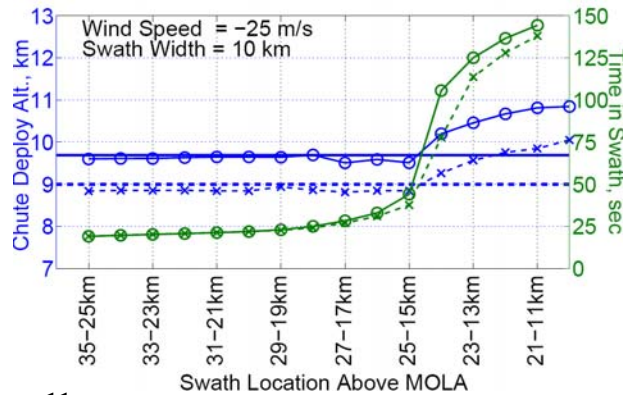
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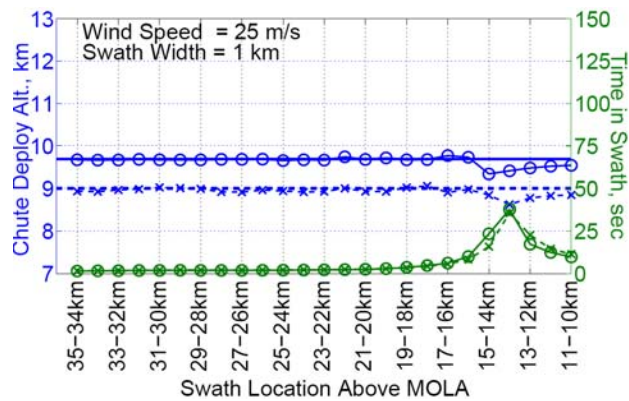


11d.

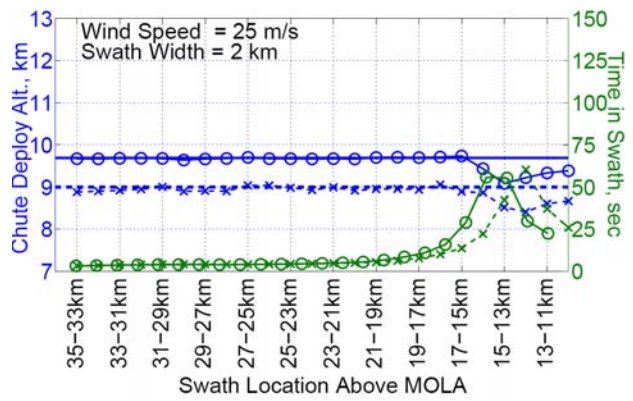


11e.

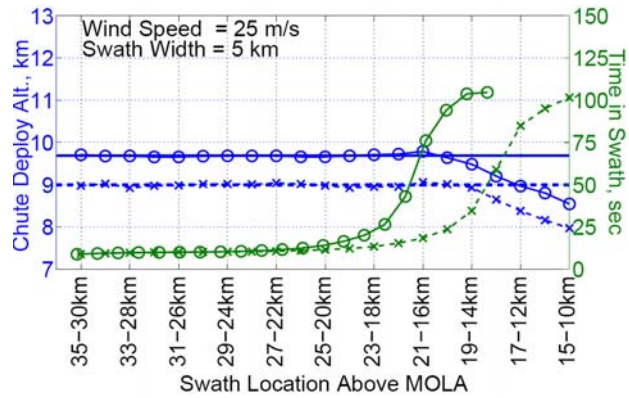
Figure 11. 25 m/s head wind. The left axis in figures a-e correspond to the final altitude at parachute deploy for each pothole considered. The nominal with nominal winds is denoted with a solid line and circles. The no wind nominal is denoted with dashed lines and an x. The axis on the right denotes the time in swath for each case.



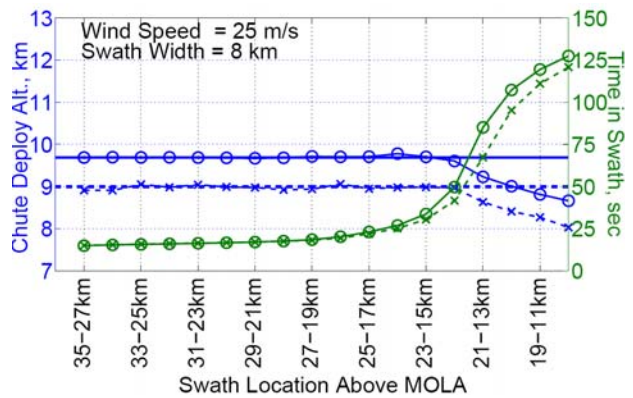
12a.



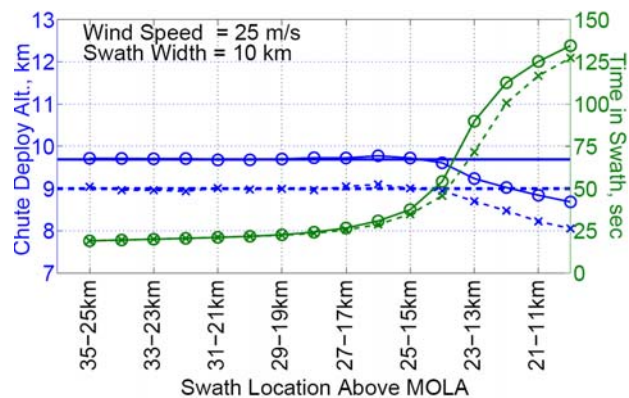
12b.



12c.

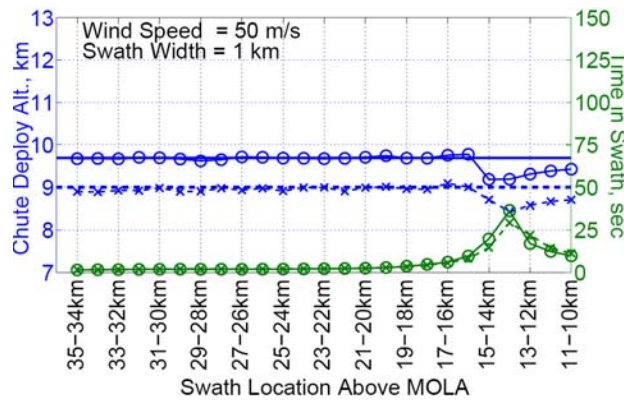


12d.

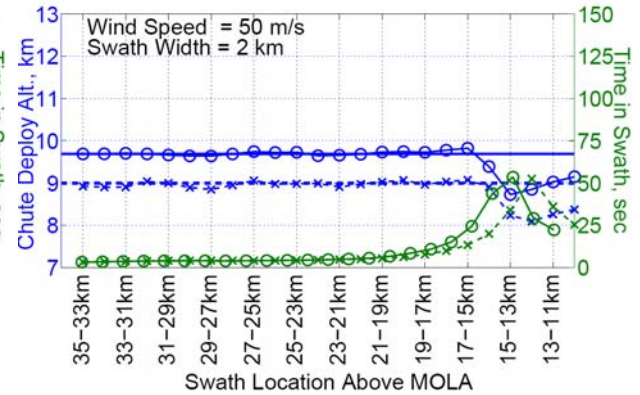


12e.

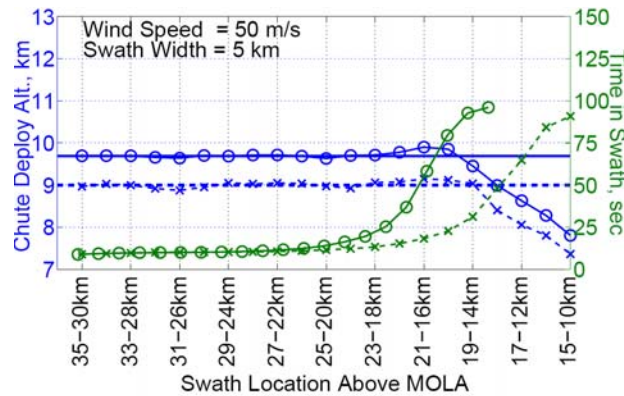
Figure 12. 25 m/s tail wind. The left axis in figures a-e correspond to the final altitude at parachute deploy for each pothole considered. The nominal with nominal winds is denoted with a solid line and circles. The no wind nominal is denoted with dashed lines and an x. The right axis denotes the time in swath for each case.



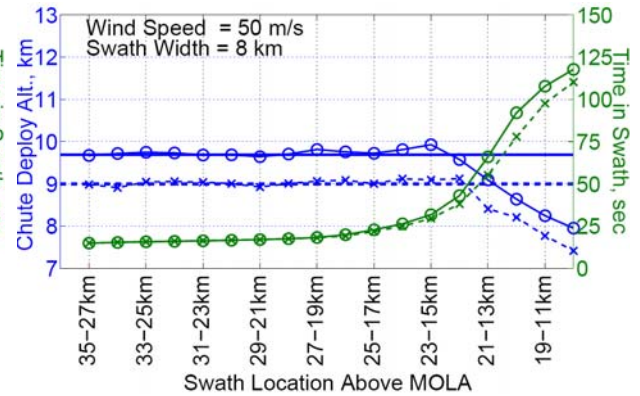
13a.



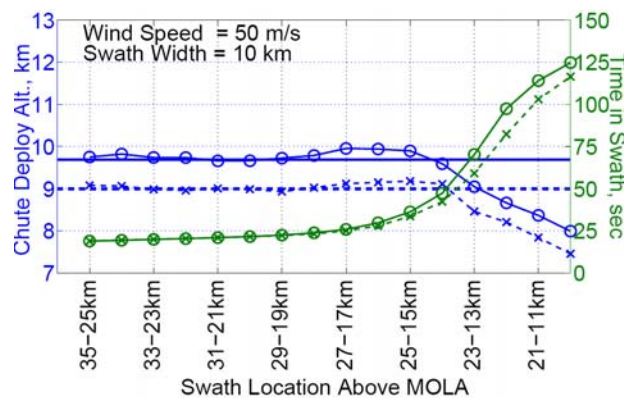
13b.



13c.

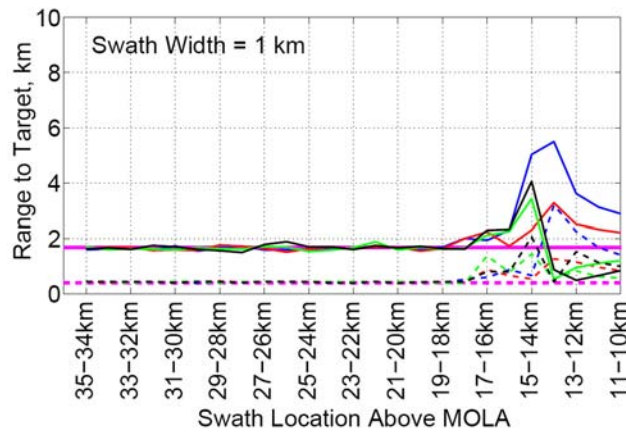


13d.

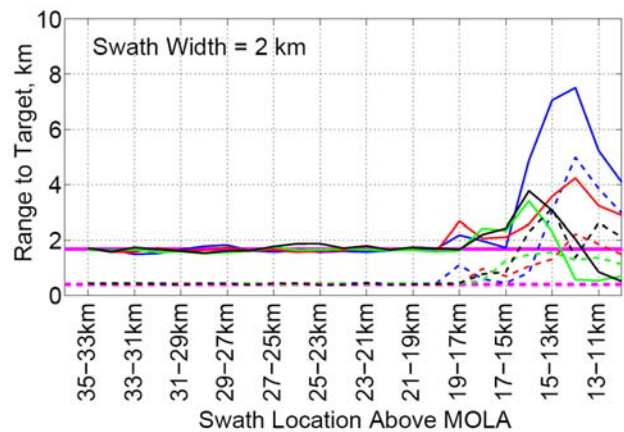


13e.

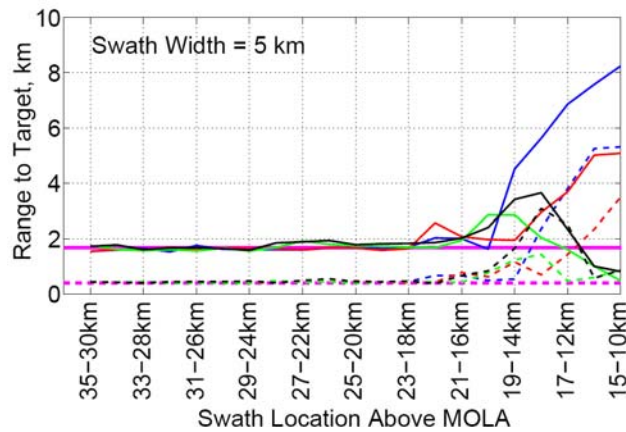
Figure 13. 50 m/s tail wind. The left axis in figures a to e correspond to the final altitude at parachute deploy for each pothole considered. The nominal with nominal winds is denoted with a solid line and circles. The no wind nominal is denoted with dashed lines and an x. The right axis denotes the time in swath for each case.



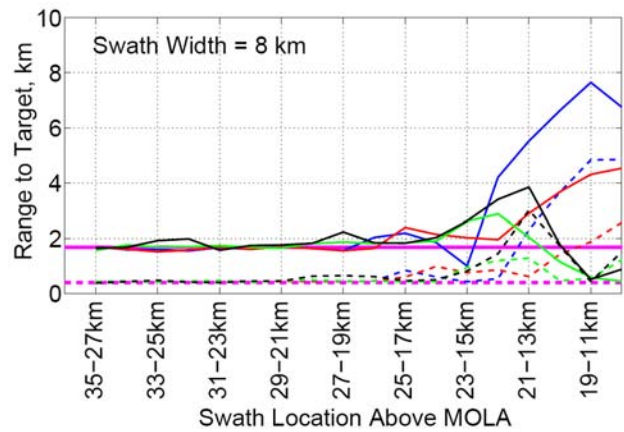
14a.



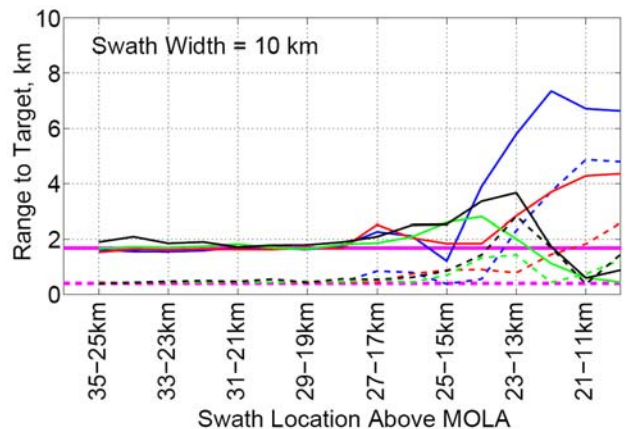
14b.



14c.



14d.



14e.

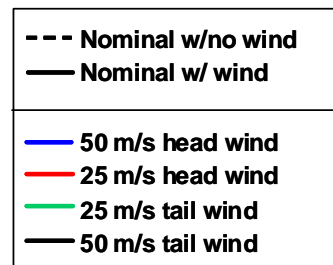


Figure 14. Range Error at Parachute Deploy for Wind Sheers. Dashed lines denote nominal trajectories with no nominal wind. Solid lines denote cases with a nominal wind.

There are no times in swath provided for wind sheers near 10 km above the areoid because the parachute is deployed prior to exiting the swath (i.e. Fig. 12c). Cases which include the nominal wind effectively increase the nominal altitude of parachute deploy by almost a kilometer. A similar offset in trends in the data persist in all performance metrics considered here. The wind sheers, as applied here also have little impact on the propellant used though it is not shown here; a maximum difference of ± 5 kg was observed, similar to the density study results. Likewise, the range error at parachute deploy, shown in Fig. 14, can be as large as 8 km for the 50 m/s head wind cases. However, in general, range errors due to winds are smaller than those observed in the density study results.

To ensure that the results were not isolated cases, a sample Monte Carlo analysis was performed on the 30% low density sheer, 1 km in width between 14 and 15 km above the MOLA areoid. It appears that the cases are not isolated because the entire Monte Carlo results are shifted in a way similar to the original case shown here.

IV. Conclusion

In general, wind or density sheers of any magnitude experienced by the vehicle above 20 km above the MOLA areoid appear to have only small effects on the entry metrics considered here; altitude at parachute deploy, propellant use and range error at parachute deploy. Below 20 km, however, long duration phenomena can have a significant effect on the state at parachute deploy. The results suggest that altitude losses of up to 3 to 4 km could be expected if a 30% low density is encountered at altitudes near 10 km, propellant use could increase by as much as 5 kg and range errors could be as large as 10 to 14 km. Initially these impacts seem relatively small until put into perspective with the entire MSL entry, descent and landing (EDL). Consider that the MSL EDL system is carrying a total propellant margin for entry of 15 kg; a 10 km range error at parachute deploy would result in a near collision with the canyon wall at Nili Fossae; and 2 km loss in altitude at parachute deploy, while insignificant if MSL lands at low altitudes sites like Gale Crater, would be challenging for a lander targeted for Nili Fossae Through. Yet, if the duration of the atmosphere phenomena are assumed to be small (less than 10 sec), then the results suggest that altitude losses of on the order of a 0.5 kilometers could be expected while propellant use and range error are minimally effected. It is important to fully understand what types of atmospheric phenomena the MSL vehicle performance is sensitive to so that the system can be made more robust. Further discussion is needed with Mars atmosphere experts to determine if the phenomena modeled herein are physically realizable at Mars and if so, the probability that the phenomena may exist on the specific day of entry.

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